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A New Method of Thermal Protection by Opposing Jet for a Hypersonic Aero-heating Strut

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This paper presents the numerical investigation of thermal protection of scramjet strut by opposing jet in supersonic stream of Mach number 6 with a hydrogen fueled scramjet strut model using CFD software. Simulation results indicate that when a small amount of fuel is injected from the nose of the strut, the bow shock is pushed away from the strut, and the heat flux is reduced in the strut, especially at the leading edge. Opposing jet forms a recirculation region near the nozzle so that the strut is covered with low temperature fuel and separated from free stream. An appropriate total pressure ratio can be used to reduce not only aerodynamic heating but also the drag of strut. It is therefore concluded that thermal protection of scramjet strut by opposing jet is one of the promising ways to protect scramjet strut in high enthalpy stream.

Keywords: thermal protection, scramjet strut, opposing jet

Introduction

Aerodynamic heating of scramjet becomes more severe [1,2] with the increasing flight Mach number, and it has attracted much attention [3,4,5] from the research community. Much work has been done on this particular aspect in recent years.

Combustor is one of the most important parts of scramjet [6]. As a usual means for fuel injection, the strut is used not only to inject fuel, but also to make the combustion stable [7]. Due to aerodynamic heating and combustion, the surface heat flux of the strut is very high. It is common to use a small strut wedge angle to reduce the drag [8], however, it leads to a high heat flux at the leading edge of a strut. So, the thermal protection of the leading edge of a strut is a problem.

Passive cooling is a common way of strut thermal protection at low Mach number, Sunami, T. et al. [9] designed a strut which was made of ablation resistant material. However, the temperature of the strut leading edge reaches 3000 K when flight Mach number is higher than 5. It is hard to find an ideal material to accommodate such a high temperature. Regenerative cooling [10] is an active way of thermal protection [11], fuel flows in the channel as coolant to absorb heat. For example, Russian scientist Semonov [12] designed a strut with an active cooling system, low temperature fuel flowed in the thin walled tubes of the strut [13]. The regenerative cooling is effective for the thermal protection of strut. But it is difficult to design tubes at the leading edge because of its small size, and so, the method could not be used for the leading edge. Brune. A [14] used transpiration cooling to protect the strut from high temperature, yet the structure was too complex. In conclusion, the thermal protection of the leading edge is the key and difficult point [15] of strut, and it is hard to protect the leading edge from aerody-

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Nomenclature

FS	arc surface of strut leading edge	Ma	Mach number of free stream
FP	windward bevel of strut	P_j	Total pressure of opposing jet
S_t	Stanton number	P_0	Total pressure of free stream.
q_w	heat flux	C	Drag coefficient,
T_{aw}	wall recovery temperature of an adiabatic wall	C_p	Pressure drag coefficient,
T_w	wall temperature	C_f	Friction drag coefficient,
ρ	density of free stream	C_d	Total drag coefficient,
C_p	Specific heat of free stream	F	Drag,
u	Velocity of free stream	$\rho V^2/2$	Dynamic air pressure at entrance,
T_∞	Temperature of free stream	A_{strut}	Windward area.
Subscripts			
j	Opposing jet	0	Free stream

namic heating. Both the drag of strut and the effect of thermal protection should be taken into consideration when a cooling system of strut is designed.

A new thermal protection method by opposing jet for a scramjet strut was presented in this paper. The mechanism of aerodynamic heating reduction by opposing jet was introduced. A scramjet strut with opposing jet model was constructed. Numerical simulation was run to verify the effectiveness of the proposed method in protecting the strut. The heat flux distribution and characteristics of the strut flow field were analyzed in this study.

Method of opposing jet

When aircraft flies in supersonic free stream, aerodynamic heating results in an ultra-high surface temperature, and its thermal environment is similar to that of a strut. Passive, semi-passive cooling or active cooling is usually used for thermal protection of strut [16-18]. In 1960s Japanese scientists began their study on the reduction of aerodynamic heating of aircraft nose by opposing jet. Finley.P.J [19] studied Mach disk recirculation region and shock wave in opposing jet flow field in 1966. Aso.S [20] studied the reduction of aerodynamic heating by opposing jet in supersonic stream.

As shown in Fig.1, a spindly nozzle is added to the leading edge of the strut. So that low temperature fuel flows through the cooling tubes to absorb heat. An opposing jet covers the whole surface of the strut, then, heat is transferred from the free stream to the strut.

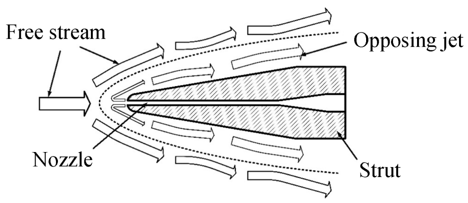


Fig. 1 Thermal protection by opposing jet

Calculation methodology

In the scramjet under study hydrogen fuel is injected from the nose of the strut to cool the strut, and then burned in the back of the combustor.

Combustor and strut configuration

As the initial work on the use of opposing jet for thermal protection of scramjet strut, only a strut without sweepback is studied through calculation. The nozzle at the leading edge is a spindly seam, and so, a 2-D simulation is used to show the characteristics of its flow field. The grid and physical model are the same as those used in Zong's study [8].

Physical model

All the meshes are generated by ICEM. The calculation is done by using Fluent (version 14.5). A density-based solver with implicit time-marching algorithm is used for simulation. A SST K-ω model with default values is used for modelling turbulence. Specific heat ratio is calculated using the simulated expressions of temperature with default value. Thermal conductivity is calculated using perturbation methods, and coefficient of viscosity is calculated using Sutherland law.

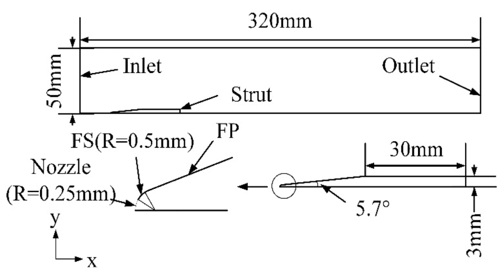


Fig. 2 Schematic diagram of analysis model and strut installation

Physical model boundary conditions

The surface temperature of the strut is a constant value for this study. The temperature is 1000K, which is near the highest temperature for metal. Adiabatic and no-slip boundary conditions are for all the wall surfaces.

The entrance condition of flight Mach number 6 is used as the combustor entrance parameters. The entrance of opposing jet is pressure-inlet.

Table 1 Initial boundary conditions

	Entrance of combustor	Entrance of opposing jet
Mach number	3.2	1.1
Total pressure (MPa)	2.7	By calculation
Static pressure (kPa)	52.7	By calculation
Total temperature(K)	1505	300

Results and Analysis

Effect of opposing jet on heat flux distribution

For this study, Stanton number [21] is used to compare each heat flux distribution. And it can be defined as:

$$St = \frac{q_w}{(T_{aw} - T_w)\rho_\infty C_{p\infty} u_\infty} \quad (1)$$

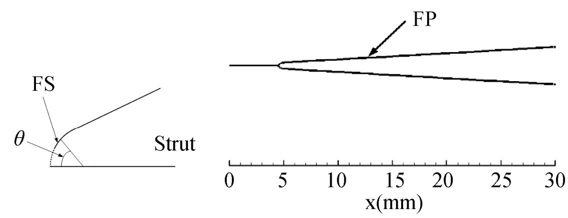
$$T_{aw} = T_\infty \left\{1 + \sqrt[3]{\Pr}\left[(\gamma - 1)/2\right]Ma_\infty^2\right\} \quad (2)$$

where S_t is the Stanton number, q_w is the heat flux, T_{aw} is wall recovery temperature of an adiabatic wall, T_w is the wall temperature, ρ_∞ is the density of free stream, $C_{p\infty}$ is the specific heat of free stream, u_∞ is the velocity of free stream, T_∞ is the temperature of free stream, Ma_∞ is the Mach number of free stream.

Angle is used to show the heat flux distribution in Fig.3a. X-coordinate was adequate to show the heat flux distribution on FP in Fig.3b. P_j is the total pressure of opposing jet, and P_0 is the total pressure of free stream.

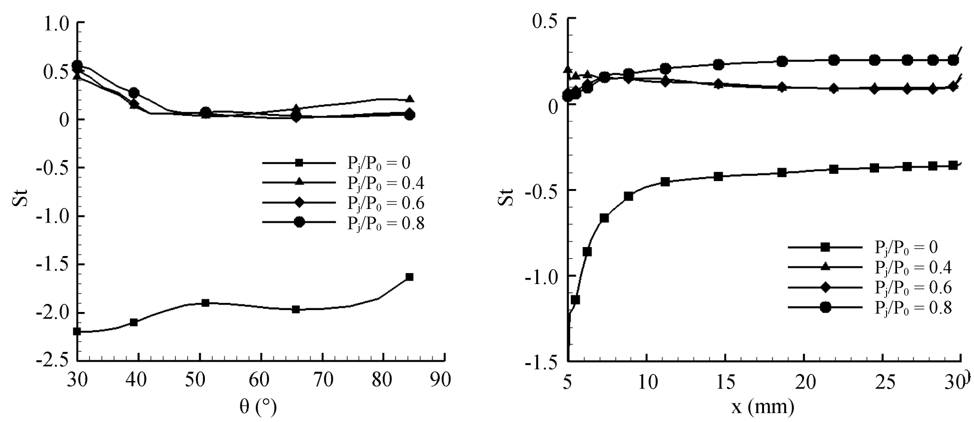
As shown in Fig.4, the heat transfer process is in the right tropism, and so the Stanton number could be either positive or negative. For this study, Stanton number is positive when heat is transferred from strut to gas, and negative when in the opposite direction. Stanton number is negative on FS and FP when there is no opposing jet, which means that heat is transferred from gas to strut. Besides, heat flux in FS is higher than that in FP, which means that the aerodynamic heating is more serious at the stagnation point of the strut. It can be seen from Fig.4 that the strut is covered with cooling fuel, and is separated from the free stream, heat is transferred from strut to gas when the temperature of fuel is lower than that of the strut. What is more, the heat flux transferred from strut to gas increases with the increasing total pressure of opposing jet in FS, and so is FP. The cooling of the strut is more effective with the increasing total pressure of opposing jet. Heat flux is directly linked to the temperature of gas around as the transfer between strut and gas around is heat convection as shown in Fig.5.

Free stream hits against the strut straightly when there is no opposing jet. The majority of kinetic energy of free stream is transferred into the internal energy on FS. The temperature around FS is more than 1400 K, and the temperature around FP is about 1000 K. Therefore, heat is transferred from free stream to the strut. The heat flux increases as the difference in temperature between FS



(a) Coordinate in FS (b) Coordinate in FP

Fig. 3 Coordinate in strut



(a) Stanton number in FS (b) Stanton number in FP

Fig. 4 Stanton number distributions in FS and FP for different total pressure ratios

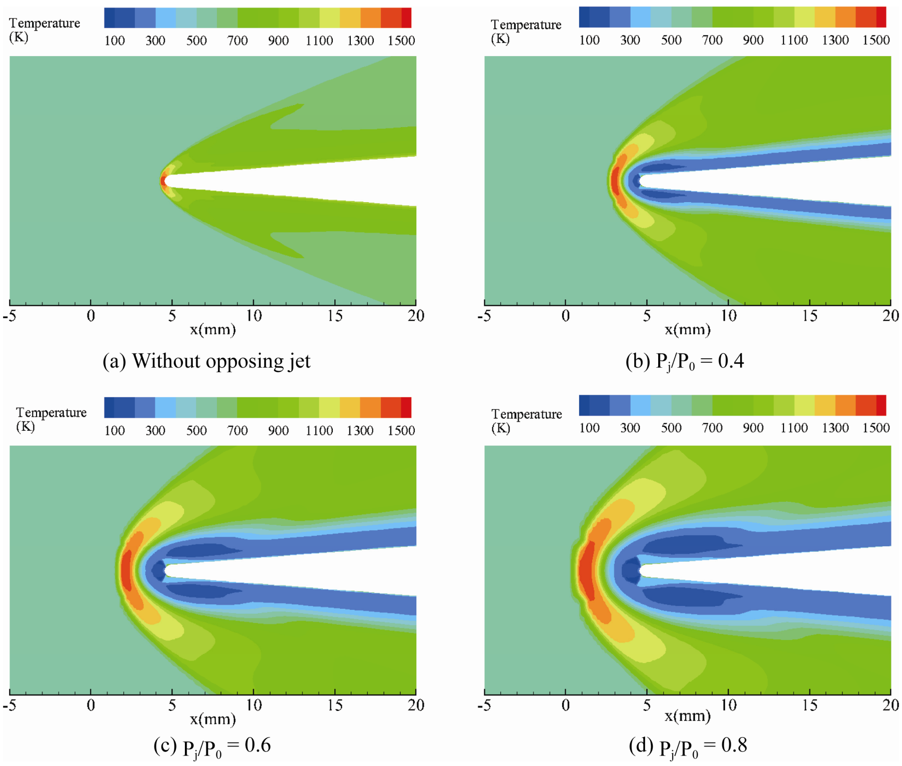


Fig. 5 Temperature contours on FS and FP at different total pressure ratios

and gas increases and so, the leading edge ablation can be easily caused. After the fuel with a total temperature of only 300K is injected from the nozzle of strut, the strut is covered with fuel because of the pressure and friction of free stream, and consequently, the heat cannot be transferred from free stream to the strut.

Effect of opposing jet on shock wave

As shown in Fig.6, a bow shock wave appears when supersonic stream hits the wedge. The stream is compressed more severely, and the temperature increases with the increasing shock wave strength. And then, the heat flux between strut and stream increases.

It can be seen from Fig.6 that the air temperature is the highest near the stagnation point when there is no opposing jet. However, the gas temperature goes down to 200 K when fuel is injected, and the peak point of temperature profiles moves away from the strut, which implies that the bow shock wave is pushed off the strut by opposing jet. The shock wave is pushed further away with the increasing total pressure ratio.

The temperature, pressure and density of gas increase suddenly after the gas passing the shock wave. The distances between the shock wave and the strut at different total pressure ratios are shown in Fig.7. The distance between the shock wave and the strut is only 0.3 mm when there is no opposing jet as shown in Fig.7. The shock wave moves away from the strut after fuel is injected. The distance is 4 mm when the total pressure is 0.8.

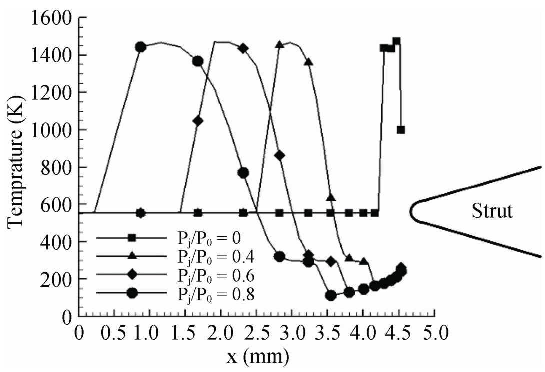


Fig. 6 Temperature profiles in front of the strut at different total pressure

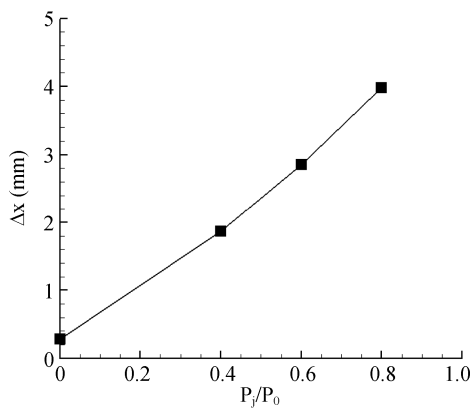


Fig. 7 Distance between strut and shock waves for different total pressure ratios

As shown in Fig.8, there is a detached bow shock wave near the leading edge of the strut when there is no opposing jet. When there is an opposing jet, there is a Mach disk in front of the strut to balance the pressure of jet with the pressure behind the detached shock wave, which grows with increasing total pressure ratio.

Effect of opposing jet on flow field

As shown in Fig.9, free stream hits the leading edge of the strut straightly and flows backward against 2 strut when there is no opposing jet. There is a recirculation region near the nozzle at the leading edge as fuel is injected from the nozzle. The recirculation region expands with the increasing total pressure ratio. The recirculation region is covered with cooling fuel, and then it reduces the aerodynamic heating on FS. The reflowing fuel flows along the strut to separate FP from free stream.

As shown in Fig.10, without opposing jet the pressure is the highest at stagnation point, and the detached shock wave from the stagnation point is the strongest. The pressure declines with increasing θ and weakening shock wave. Compared with the case without opposing jet, the pressure on FS is 0.05 MPa lower, and the pressure is far less than that in the case of without opposing jet, which implies the bow shock wave is weakened by opposing jet.

Effect of opposing jet on drag of strut

Low drag can reduce the loss of specific impulse and obtain a higher thrust. The drag coefficient of strut is used to study the effect of opposing jet on the drag of strut. The drag coefficient can be defined as:

$$C = \frac{F}{\frac{1}{2}\rho V^2 A_{strut}} \tag{3}$$

where C is the drag coefficient, C_p is the pressure drag coefficient, C_f is the friction drag coefficient, C_d is the total drag coefficient, F is the drag, $\rho V^2/2$ is the dynamic air pressure at entrance, A_{strut} is the windward area.

As shown in Fig.11, the total drag coefficient at different total pressure ratios is smaller than that for the strut without opposing jet. The total drag coefficient is the smallest when the total pressure ratio is 0.6, which is reduced by about 28.5%. The pressure drag coefficient gradually declines as the total pressure ratio increases. Friction drag coefficient changes slightly with the increasing total pressure, and it was higher than that in the case of no opposing jet when the total pressure ratio is 0.8.

Opposing jet can cause a recirculation region near the nozzle of strut. The pressure of gas in the recirculation region is lower than the pressure of free stream, and so, the pressure drag of strut declines. As the total pressure ratio increases, the recirculation region expands, and the pressure drag of strut declines further. A proper total pressure ratio can reduce not only the aerodynamic heating but also the drag of strut.

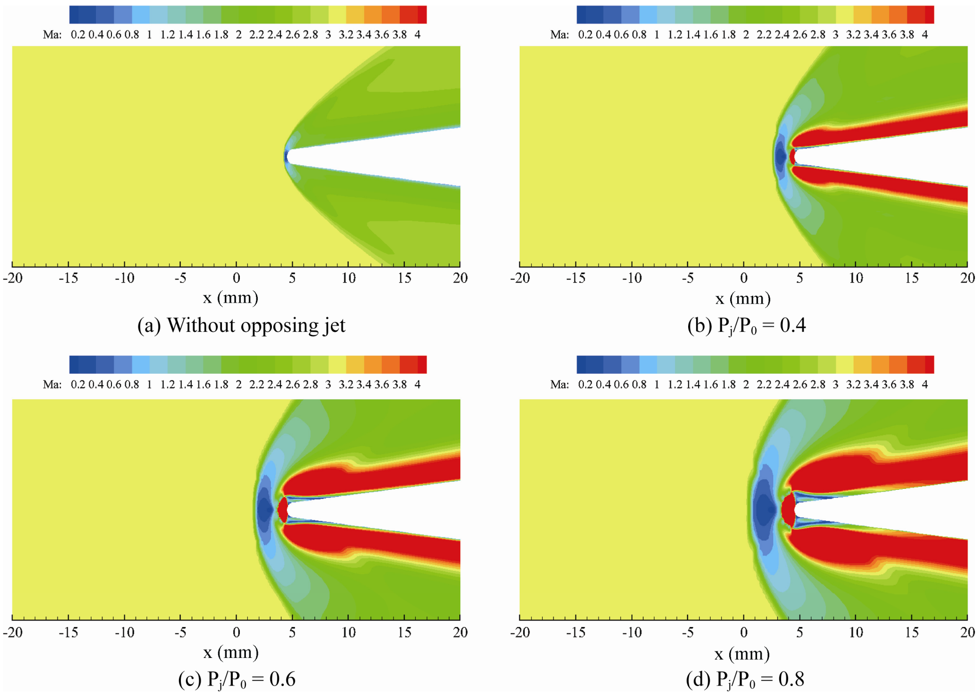
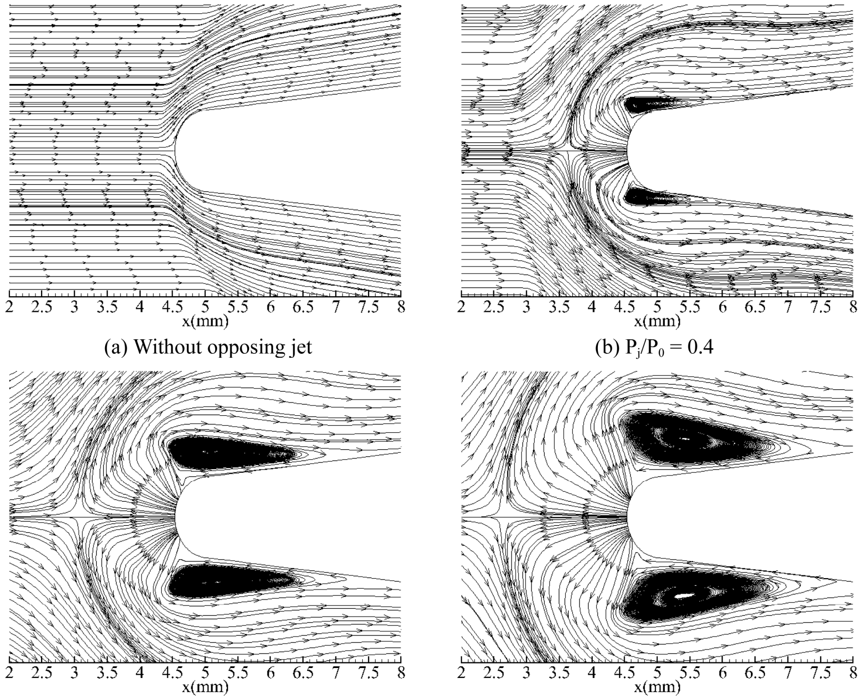


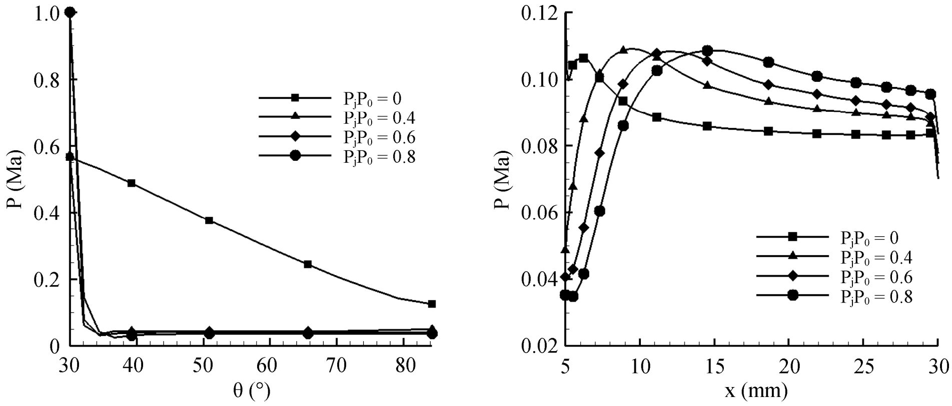
Fig. 8 Mach number contours of flow field at different total pressure ratios



(a) Without opposing jet (b) $P_j/P_0 = 0.4$

(c) $P_j/P_0 = 0.6$ (d) $P_j/P_0 = 0.8$

Fig. 9 Streamlines near leading edge of the strut at different total pressure ratios



(a) FS (b) FP

Fig. 10 Pressure distributions on FS and FP at different total pressure ratios

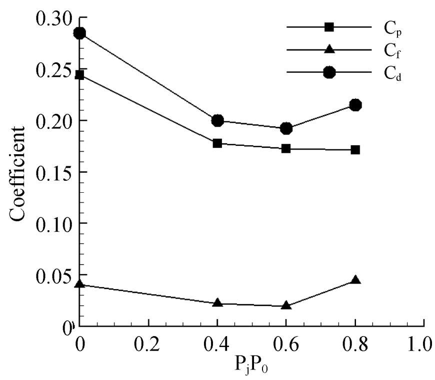


Fig. 11 Drag coefficient of the flow fields at different total pressure ratios

Conclusions

It can be seen from the presentation above that when a small amount of fuel is injected from the nose of strut, the bow shock is pushed away from the strut, and the heat flux is reduced in the strut, especially in the leading edge. A recirculation region is formed near the nozzle so that the strut is covered with low temperature fuel and separated from free stream. The heat flux from strut to fuel increases with the increasing total pressure ratio, and an appropriate total pressure ratio can be used to reduce not only aerodynamic heating but also the drag of strut. It is therefore concluded that thermal protection of scramjet

strut by opposing jet is one of the promising ways to protect scramjet strut in high enthalpy stream.

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